Near-Bottom Turbulence and Sediment Resuspension Induced by Nonlinear Internal Waves

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LONG-TERM GOALS

The long term goal of this work is to develop a fundamental understanding and predictive capability of the underlying physics of the interaction of nonlinear internal waves (NLIWs) with the continental shelf seafloor over a broad range of environmental conditions. We are particularly interested in how such interactions impact underwater optics and acoustics and shelf energetics and ecology by stimulating enhanced bottom boundary layer (BBL) turbulence and particulate resuspension leading to benthic nepheloid layer (BNL) formation.

OBJECTIVES

The specific objectives are:

- Using Large Eddy Simulations (LES), investigate the structural transition to turbulence within the separated BBL layer under a NLIW of depression and quantify the resulting NLIW energy losses.
- By means of Lagrangian coherent structure (LCS) theory, identify mechanisms for the capturing of nearbed particles by the BBL-turbulence and their transport/deposition into BNLs.
- Analyze field observations from the New Jersey shelf to identify the applicability of hypothesized BBL physics and flesh out the underlying fluid mechanics from the field data.

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APPROACH

Our approach relies on implicit 3-D Large Eddy Simulation (LES) based on spectral multidomain solver developed by P.I. Diamessis (Diamessis et al. 2005). This code has been successfully applied to a number of computational stratified flow process studies in 2-D and 3-D (Diamessis et al. 2011, Diamessis et al. 2013), including (Diamessis and Redekopp 2006, Sakai et al. 2012). It employs a uniform periodic (Fourier-based) grid in the along-wave direction and a multidomain Legendre-polynomial-based discretization, equipped with a penalty scheme, in the vertical.

Our problem geometry considers a mode-1 wave of *depression* fixed in a frame of reference moving with the NLIW's phase speed through a uniform-depth waveguide (figure 1). The background stratification acposs the full water column consists of a two uniform density layers separated by a finite-thickness pycnocline (figure 1). If required, the wave propagates against an oncoming barotropic background current which has, at the end, its own idealized Blasius-like boundary layer. As the wave is kept fixed in time, we solve for the perturbation to this wavefield that develops through the mismatch between the non-zero wave velocity field and no-slip condition at the bed (Diamessis and Redekopp 2006). To maximize resolution of the 3-D turbulence in the NLIW-induced BBL, our computational domain is a truncated in the vertical direction. A detailed view of the computational domain with the appropriate boundary conditions is shown in Figure 1.

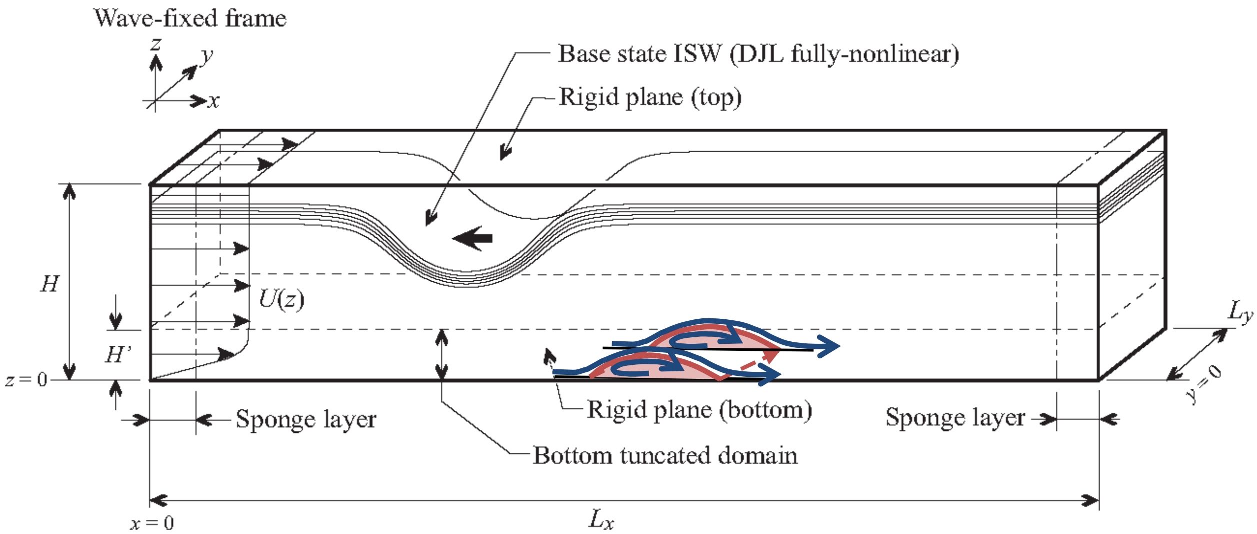

Figure 1: Schematic of flow configuration used in Large Eddy Simulations. The separation bubble (near-bed recirculation zone) is highlighted.

Finally, our particle-tracking tools revolve around libraries built by co-P.I. Jacobs based on a higher-order accuracy Eulerian-Lagrangian (EL) approach (Jacobs and Hesthaven 2006, Jacobs and Don 2009). These tools have been used by the co-P.I. to determine particle-laden flow with relevance to liquid-fuel combustors. Originally developed for a discontinuous Galerkin-based flow solver for the compressible Navier-Stokes equations, these tools are directly compatible and implementable within the incompressible spectral multidomain method that the P.I. has developed. The necessary implementation will be initiated in late Fall 2013 by a recently arrived Ph.D. student.

WORK COMPLETED

As indicated in last year's report, significant effort was put into configuring the computational domain for maximum efficiency in the actual 3-D simulations. Specific tasks included investigating the role and structure of a background current, the impact of vertically truncating the domain at different hieght, the associated boundary conditions at the top of the truncated domain and the sensitivity of the 2-D boundary layer to noise insertion. We reiterate that in the absence of an oncoming current, the BBL separates in the rear end of the wave but does not reattach ; instead a near-bed jet forms.In contrast, in the presence of an oncoming current, the BBL does reattach forming a separation bubble (see Fig. 1) which is prone to a particular self-triggered shear instability in 2-D, known as a global instability, which results in a near-bed vortex wake (Diamessis and Redekopp 2006). No such instability is observed in the no current case, presumably due to the different instability properties of the base flow ; persistent background forcing is needed to see any shed vortices. This finding is contrary to the observations in laboratory experiments (Carr et al. 2008), giving rise to many open questions.

3-D simulations began in early Fall 2012 with one focused run with a current of strength $U_0=0.1c$, where c is the wave phase speed. Transition to turbulence with a pre-existing separation bubble is a more familiar starting point for us. For the above run, the wave-based Reynolds number, defined in terms of the total depth of the water column, H, is $Re_W=Hc/\nu=1.6\times10^5$, i.e. 60% larger than that of the above lab experiments. The pycnocline is centered at a depth of $(1/8.5)H$. The NLIW amplitude is 0.346H. Choice of lateral domain dimensions has been guided by previous work on stratified shear layers (Smyth and Moum 2000). A resolution of 8192×64×251 is used which captures more than 0.1 wall unit in the vertical and resolves very well (though not completely) the turbulence in the along-wave and transverese directions.The simulation was run on 128 processors on a DoD HPCMP Open Research System.

Based on the experience of the co-P.I. with engineering turbulent separating boundary layers (backward facing step, combustor) we sought to trigger transition to turbulence in the BBL by inserting a patch of carefully designed "synthetic turbulence" in the fully developed separation bubble. One expects Navier-Stokes turbulence to form and the separation bubble to drive a *persistent and self-sustained* 3-D near-bed vortex wake. The run took 2.5 months, which is 2 months longer than we had anticipated as small-scale 3-D motions in the BBL impose significant constraints on the vertical CFL number. Much to our frustration, we found that the separation bubble breaks down into a temporally evolving near-bed turbulent shear layer (i.e. a train of K-H billows), which simply advect downstream of the wave. The separation bubble relaminarizes and no self-sustained turbulent wake is observed. It is unclear to us why this is the case but we are inclined to attribute it to the very high-aspect ratio of the separation bubble with respect to it engineering counterparts.

In our quest for numerically generating near-bed self-sustained turbulence, we turned to a particular study in the aerodynamics literature (Jones et al. 2008). Following their example, we introduced a volume forcing at the top edge and rear end of the separation bubble (Fig. 2). Significant effort was invested in determining the optimal location and amplitude of the volume forcing.The separating streamline acts as a barrier towards any mass-transport towards the bed, thus leaving the bubble intact and able to undergo the aforementioned 2-D global instability and vortex shedding. The forcing pulsates at the frequency of the 2-D instability and with a lateral spectrum of wavenumbers. In that spectrum, the dominant mode is the transverse wavenumber of the gravest secondary instability mode.

This dominant mode was estimated after extensive test runs on 128 procs. with 16 grid-points. According to Jones et al. 2008, the perturbations generated by the forcing travel downstream, trigger turbulence transition and the near-bed turbulence is expected to catch up with the shed vortices to produce the desired near-bed self-sustained wake.

We have three ongoing simulations, for the same wave as above with different oncoming current strengths. The one started first, in April, has an oncoming current strength of $U_0 = 0.4c$. We recently turned-off the volume forcing to determine the presence of self-sustained near-bed turbulent wake. Results are reported in the next section. Two other were initiated in early June with $U_0 = 0.1c$ and 0. So far we have consumed $O(10^6)$ CPU hours.

We would like to reiterate that, although not comparable to the demands of a field deployment, the simulations of the very complex NLIW-induced 3-D BBLs are non-trivial in terms of both cost and conceptual implementation. We have contributed significant insight in this direction along with an already large dataset that is the subject of undergoing and future analysis.

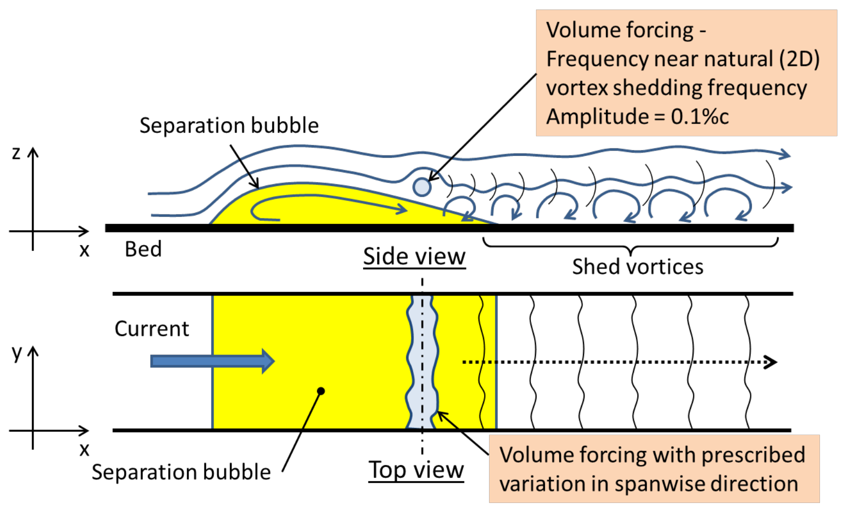

Figure 2: Schematic of volume forcing technique used to transition BBL under NLIW into turbulence. The turbulence generated by the forcing propagates downstream and overtakes the 2-D shed vortices to ultimately establish a self-sustained near-bed turbulent wake.

RESULTS

We have acquired significant data from our ongoing costly yet very data-rich simulations. Analysis is ongoing. In what follows, we present some representative preliminary results for the first of our three ongoing simulations.

First, spanwise spatial correlation functions have shown that our current lateral domain dimension supports 4-6 transverse integral scales confirming our choice of a sufficiently wide domain (not shown here). Figure 3 shows the evolution of the NLIW-induced BBL downstream of the separation bubble in terms of the dominant coherent structures (as educed by the well-known λ_2 criterion). Immediately downstream of the volume forcing region, one sees spanwise vortices perturbed by the gravest

transverse instability mode. Further downstream, trains of hairpin vortices, typical of transitional boundary layers have developed. At the next visualization window in the along-wave direction, one sees an increasingly less-organized structure, where the near-bed shear stress maximizes its value. Finally, in the last window a fully developed turbulent flow has almost been established. The turbulent kinetic energy spectra in Fig. 4 show the presence of a distinct inertial range confirming that fully developed turbulence is in the process of being established. Note that the advancement of the simulation to this point has been extremely painstaking.

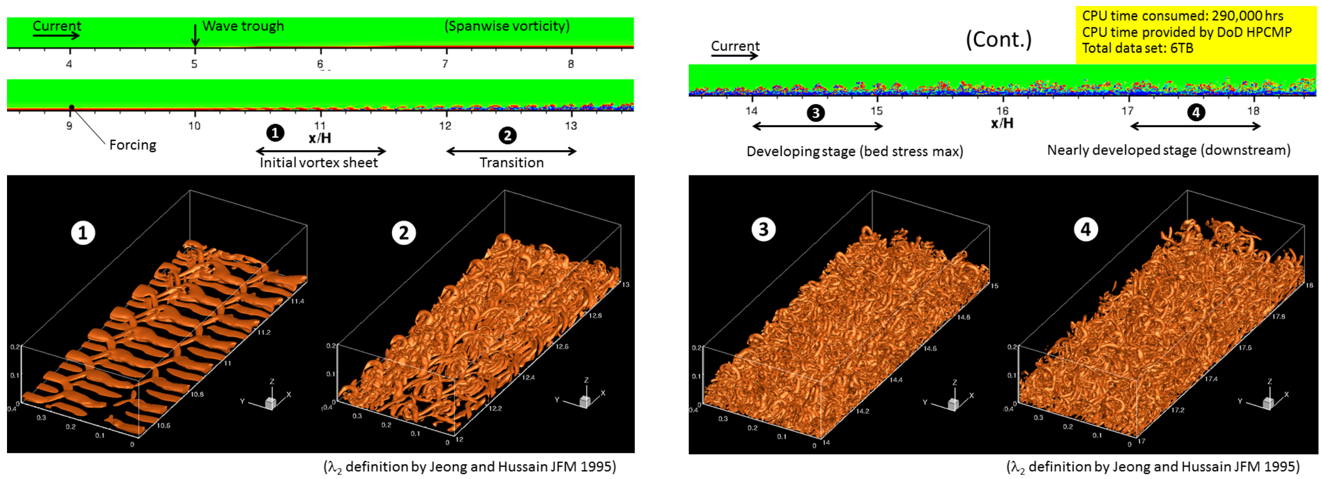

Figure 3: Transition to turbulence in a volume-forced NLIW-induced BBL. The base state NLIW has amplitude of 0.346H and the wave Reynolds number is Re_W=cH/ν=1.6×10^5, where H is the water column depth and c the NLIW phase speed. Snapshots show coherent turbulent structures along intervals at different, along-wave, x/H locations, downstream of the wave trough, as indicated by the colored contour plots above the isosurface plots.

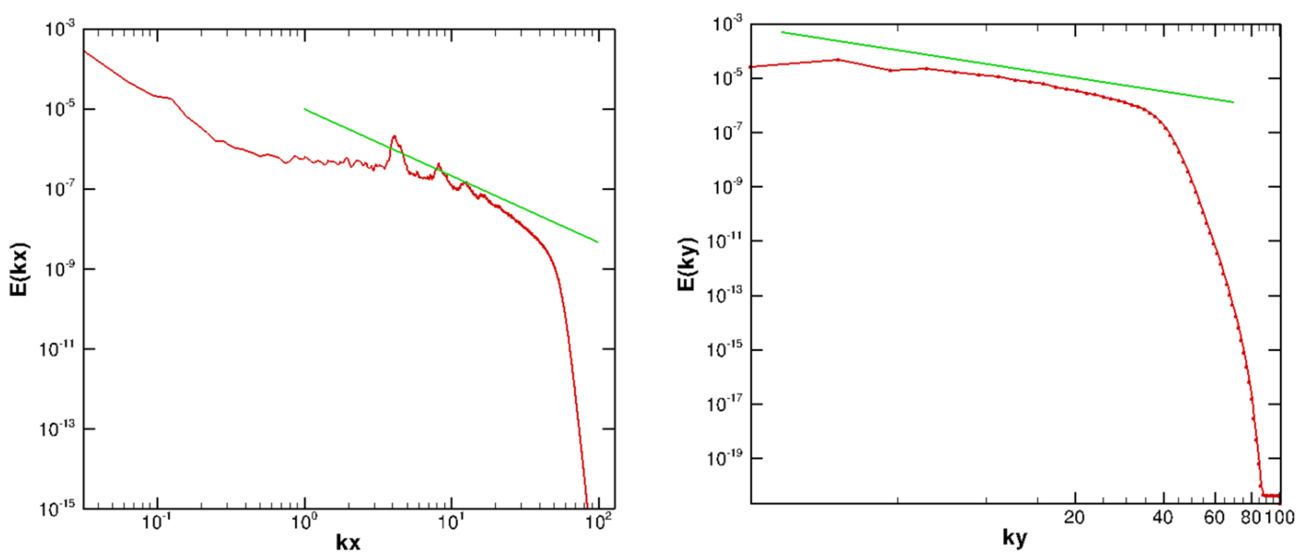

Figure 4: Turbulent kinetic energy spectra sampled in the nearly fully developed turbulence region of the BBL driven by the NLIW of Fig. 3. (zone 4). Left: Streamwise spectra. Right: spanwise spectra. The green line represents the Kolmogorov -5/3 power law.

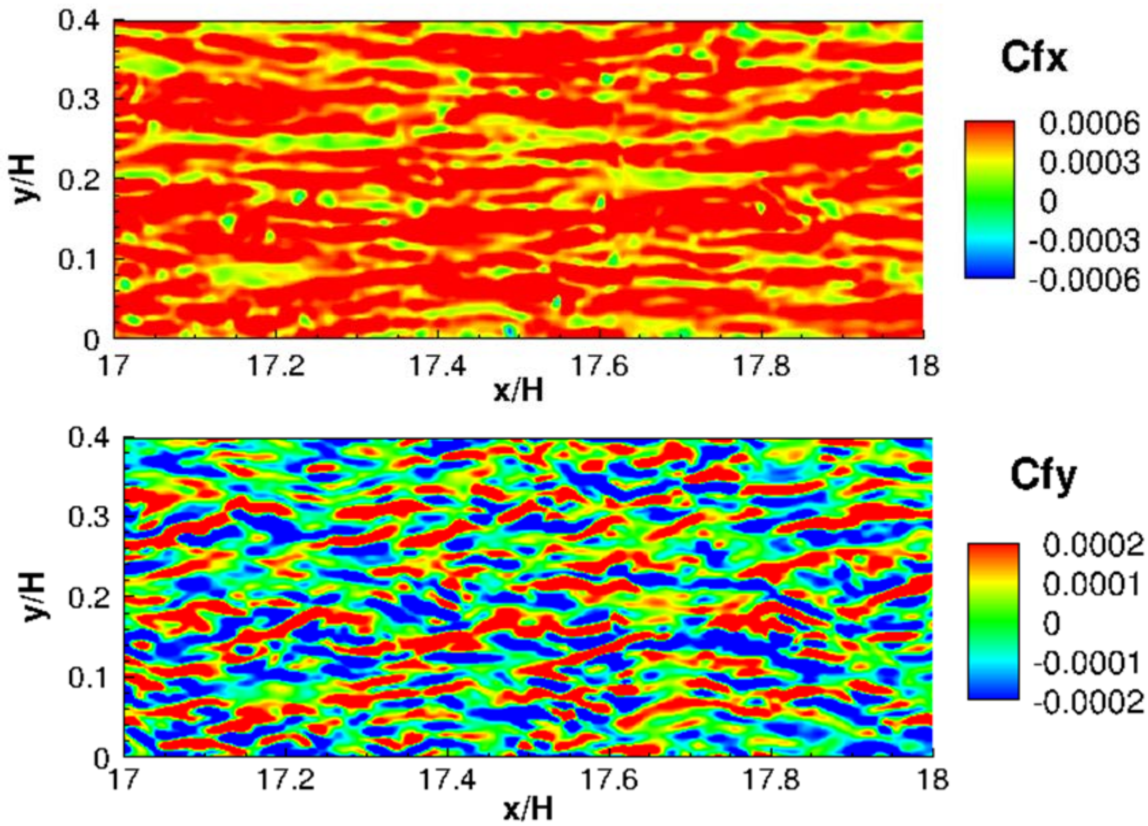

Figure 5: Snapshots of the bottom shear stress coefficients (component of shear stress field normalized by $\rho_0 c/2$, where ρ_0 is the reference density of water) corresponding to the nearly developed turbulent stage (zone 4 in Fig. 3) of the BBL driven by the NLIW of Fig. 3. Top: along-wave stress field ; Bottom: transverse stress coefficient.

The bottom shear stress field, quantified by the corresponding non-dimensional coefficients, is shown in Fig. 5 for both its streamwise and spanwise components. Streaky structures typical of turbulent boundary layers are immediately evident, with the streamwise component dominated by positive values with occasional islands of negative ones. We are currently exploring the implications of these shear-stress fields for particle resuspension in the context of particular types of pick-up functions. Moreover, the bottom shear stress field is central to the estimation of NLIW-induced bottom drag and dissipation and the development of parameterizations based on the wave-induced current (Shroyer et al. 2010 and 2011) and relevant work will soon be underway.

Beyond the investigation of whether self-sustained turbulence is indeed possible upon turn-off of the volume forcing, ongoing and near-future work involves the examination of the pressure field at the bed and its potential correlation with the bottom shear stress field and further probing of any deviations of the mean velocity profile from the law of the wall I. The generation of metrics from virtual Eulerian sensors will also be pursued and will involve vertical line cuts and at-a-point timeseries in a fixed frame of reference under the passing wave to provide signatures one might identify in ADCP or ADV data, respectively. We have begun drafting a journal article which we anticipate to submit in Spring 2014.

IMPACT/APPLICATIONS

The accurate representation of the structure and magnitude of shear stress field field in the NLIW footprint and accurate estimation of the NLIW energy losses due to bottom interactions will allow the formulation of improved subgrid-scale parameterizations of energy dissipation and bottom boundary conditions for larger-scale operational forecasting models used to simulate environments with high NLIW activity. An enhanced understanding of the underlying physics of the NLIW-driven BBL also provides critical insight on how the bottom shear stress and pressure fields conspire to generate high-amplitude sandwaves, such as those observed in the South China Sea, which can pose significant challenges in efforts of acoustic bathymetry mapping. Finally, the generated resuspended particle distributions under NLIWs, a reliable proxy of BNLs, can be used to quantify the transmission or backscatter of optical/acoustic signals of importance to remote sensing efforts and near-bed SONAR operation.

RELATED PROJECTS

Funded, by an NSF-CAREER award in Physical Oceanography, the P.I. is refining a quadrilateral SMPM code, originally used in this project, to account for variable bathymetry. This new code will be used to study the shoaling of NLIWs in both canonical configurations and domains with bathymetry replicating the South China Sea (SCS). The physical phenomenon of interest is the formation of trapped cores in shoaling waves which involve comparison with field data from Dr. Ren-Chieh Lien of APL-U. Washington obtained in the SCS region. Supported by the CAREER award and a code 33 O.N.R. grant, and in collaboration with Dr. Scott Wunsch of the Applied Physics Lab at Johns Hopkins University and a recently graduated undergraduate student, the P.I. recently submitted an article on the nonlinear generation of harmonics during the impact of an internal wave beam on a model sharp oceanic pycnocline and the associated interfacial wave generation (Diamessis et al. 2013). The same O.N.R. code 33 funds primarily support ongoing work on the internal wave field radiated by stratified turbulent wakes and its (sub)surface signature (Abdilghanie and Diamessis 2013, Zhou and Diamessis 2013). Finally, in collaboration with Prof. Luis Parras at the U. of Malaga, Spain, the P.I. is supervising a student, co-advised with Prof. Phil Liu (Civil and Env. Eng., Cornell), working on 2-D and 3-D instability analysis of the BBL under long surface solitary waves.

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PUBLICATIONS

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Zhou, Q. and Diamessis, P.J. 2013. Reflection of an Internal GravityWave Beam off a Horizontal Free-Slip Surface , ***Phys. Fluids*** ; 25: Article 033601.

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HONORS/AWARDS/PRIZES

Sumedh Joshi, an applied mathematics Ph.D. student (not supported by this grant) at Cornell supervised by the P.I. won a 3-year NSDEG graduate fellowship which came into effect in Fall 2012. The fellowship supports the investigation of sound propagation through shoaling NLIWs using the deformed quadrilateral spectral multidomain code whose development he will soon finish. This code will be coupled to a 3-D spectral element acoustics model.